

Supporting Information Binder, Crone, Haug, Menz, Kirsch

Direct Carbocyclization of Aldehydes with Alkynes: Combining Gold Catalysis with Aminocatalysis

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Supporting Information

Representative experimental procedures for catalytic formation of **2** and **3**, and copies of ¹H and ¹³C NMR of compounds **3a–3g**, **2h–2k**, **5**, **8**, and **9**.

General experimental details: All commercially available chemicals were used without further purification. ¹H NMR spectra were obtained on Bruker 500 MHz FT-NMR, 360 MHz FT-NMR and 250 MHz FT-NMR spectrometers. ¹³C NMR spectra were recorded at 90.6 MHz. Chemical shifts are reported in ppm relative to solvent signal. Multiplicity is indicated as follows: s (singlet); d (doublet); t (triplet); m (multiplet); dd (doublet of doublets). High resolution mass spectra and EI were determined on a Finnigan MAT 95S and MAT 8200. Flash chromatography was performed with E. Merck silica gel (43–60 µm). The eluent used is reported in parentheses (P = pentanes). Thin-layer chromatography (TLC) was performed on precoated glass-backed plates (Merck Kieselgel 60 F₂₅₄), and components were visualized by observation under UV light or by treating the plates with KMnO₄/H₂SO₄ followed by heating.

All formyl alkynes **1** were obtained following a general approached as described by others.¹

¹ Buisine, O.; Aubert, C.; Malacria, M. *Chem. Eur. J.* **2001**, 7, 3517.

General Procedures for the Cyclization Reactions

General Procedure 1 (Synthesis of **2h**; Table 2, entry 7): A solution of **1h** (100 mg, 0.42 mmol) and (*c*-C₆H₁₁)(*i*-Pr)NH (20 mol %, 12 mg) in CDCl₃ (0.4 mL) was added to [(Ph₃PAu)₃O]BF₄ (7.5 mol %, 45 mg), and the reaction vial was sealed, protected from light, and stirred at 70 °C for 18 h (until ¹H NMR analysis of the reaction mixture indicated complete conversion). The mixture was concentrated under reduced pressure. Purification of the residue by flash chromatography on silica gel (pentanes/EtOAc 95:5) gave **2h** as a colorless oil (71mg, 0.30 mmol, 71%). *R*_f = 0.48 (pentanes/ EtOAc 90:10).

General Procedure 2 (Synthesis of **3a**; Table 1, entry 5): A solution of **1a** (90 mg, 0.40 mmol) and (*i*-Pr)₂NH (20 mol %, 8 mg; added as a 0.1 M stock solution) in CDCl₃ (0.4 mL) was added to a mixture of AgSbF₆ (11 mg, 10 mol%) and PPh₃AuCl (16 mg, 10 mol%), and the reaction vial was sealed, protected from light, and stirred at 70 °C for 6 h (until TLC analysis of the reaction mixture indicated complete conversion). The mixture was concentrated under reduced pressure. Purification of the residue by flash chromatography on silica gel (pentanes/Et₂O 70:30) gave **3a** as a colorless oil (74 mg, 0.33 mmol, 82%). *R*_f = 0.2 (pentanes/ EtOAc 60:40).

Compound Characterization Data

Dimethyl 3-formyl-4-methylcyclopent-3-ene-1,1-dicarboxylate (**3a**)

¹H NMR (360 MHz, CDCl₃): δ = 2.14 (s, 3 H), 3.23 (s, 4 H), 3.74 (s, 6 H), 9.93 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.0, 38.8, 47.8, 53.2, 56.8, 135.2, 157.5, 171.9, 187.2; LRMS (EI): 226 (35%) [M⁺], 195 (46%), 168 (100%), 135 (93%), 107 (98%), 79 (76%); HRMS 226.0840 [226.0841 calcd for C₁₁H₁₄O₅(M⁺)].

4,4-Bis((*tert*-butyldiphenylsilyloxy)methyl)-2-methylcyclopent-1-enecarbaldehyde (**3b**)

¹H NMR (360 MHz, CDCl₃): δ = 1.03 (s, 18 H), 2.00 (s, 3 H), 2.42 (s, 2 H), 2.45 (s, 2 H), 3.58–3.66 (m, 4 H), 7.20–7.36 (m, 8 H), 7.38–7.44 (m, 4 H), 7.59–7.66 (m, 8 H), 9.91 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.4, 19.5, 27.1, 36.1, 46.0, 47.7, 66.8, 127.8, 129.8, 133.6, 133.7, 135.8, 136.9, 160.8, 188.2; LRMS (EI): 589 (50%) [M⁺-C₄H₉], 333 (32%), 257 (21%), 197 (37%), 135 (100%), 91 (28%); HRMS 589.2600 [589.2594 calcd for C₃₇H₄₁O₃Si (M⁺-C₄H₉)].

4,4-Bis(methoxymethyl)-2-methylcyclopent-1-enecarbaldehyde (3c)

¹H NMR (360 MHz, CDCl₃): δ = 2.10 (s, 3 H), 2.41–2.44 (m, 2 H), 2.47–2.51 (m, 2 H), 3.22–3.29 (m, 4 H), 3.30 (s, 6 H), 9.96 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.4, 36.8, 44.8, 46.7, 59.4, 76.6, 136.6, 160.4, 188.3; LRMS (EI): 198 (4%) [M⁺], 153 (67%), 137 (25%), 121 (47%), 45 (100%); HRMS 198.1257 [198.1256 calcd for C₁₁H₁₈O₃(M⁺)].

4,4-Bis(benzyloxymethyl)-2-methylcyclopent-1-enecarbaldehyde (3d)

¹H NMR (360 MHz, CDCl₃): δ = 2.09 (s, 3 H), 2.50 (s, 2 H), 2.53 (s, 2 H), 3.37–3.44 (m, 4 H), 4.51 (s, 4 H), 7.24–7.36 (m, 10 H), 9.96 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.4, 36.9, 45.0, 46.9, 73.4, 73.8, 127.6, 127.6, 128.4, 136.7, 138.7, 160.5, 188.3; LRMS (EI): 350 (6%) [M⁺], 259 (10%), 229 (23%), 121 (15%), 91 (100%); HRMS 350.1884 [350.1882 calcd for C₂₃H₂₆O₃(M⁺)].

4,4-Diacetyl-2-methylcyclopent-1-enecarbaldehyde (3e)

¹H NMR (360 MHz, CDCl₃): δ = 2.12 (s, 9 H), 3.10 (s, 4 H), 9.87 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.1, 26.4, 35.4, 44.4, 71.2, 134.9, 157.7, 187.3, 203.6; LRMS (EI): 151 (50%) [M⁺-C₂H₃O], 123 (11%), 109 (21%), 81 (26%), 43 (100%); HRMS 151.0758 [151.0759 calcd for C₉H₁₁O₂(M⁺-C₂H₃O)].

Ethyl 1-cyano-3-formyl-4-methylcyclopent-3-enecarboxylate (3f)

¹H NMR (360 MHz, CDCl₃): δ = 1.34 (t, J = 7.2 Hz, 3 H), 2.19 (s, 3 H), 3.14–3.44 (m, 4 H), 4.29 (q, J = 7.2 Hz, 2 H), 9.95 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.0, 14.1, 42.2, 43.8, 49.8, 63.6, 120.2, 134.4, 156.1, 168.4, 186.5; LRMS (EI): 207 (10%) [M⁺], 189 (8%), 134 (100%), 106 (36%), 79 (27%); HRMS 207.0897 [207.0895 calcd for C₁₁H₁₃NO₃(M⁺)].

3-Methyl-1*H*-indene-2-carbaldehyde (3g)

¹H NMR (360 MHz, CDCl₃): δ = 1.57 (t, J = 2.3 Hz, 3 H), 3.64 (d, J = 2.3 Hz, 2 H), 7.38–7.45 (m, 2 H), 7.52–7.55 (m, 1 H), 7.58–7.60 (m, 1 H), 10.24 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 10.9, 35.9, 121.8, 124.7, 127.1, 129.3, 139.7, 144.5, 144.9, 156.0, 187.3; LRMS (EI): 172 (52%) [M⁺], 143 (74%), 128 (100%), 115 (30%); LRMS (EI): 158 (77%) [M⁺], 130 (73%), 129 (100%), 115 (60%); HRMS: 158.0731 [158.0732 calcd for C₁₁H₁₀O(M⁺)].

Dimethyl 3-formyl-4-methylenecyclopentane-1,1-dicarboxylate (2h)

¹H NMR (250 MHz, CDCl₃): δ = 1.26 (s, 3 H), 2.23 (d, *J* = 14.0 Hz, 1 H), 2.92–3.07 (m, 3 H), 3.73 (s, 3 H), 3.74 (s, 3 H), 4.95 (app. t, *J* = 2.2 Hz, 1 H), 5.22 (app. t, *J* = 1.9 Hz, 1 H), 9.29 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 21.8, 40.5, 41.2, 53.1, 53.1, 56.9, 58.1, 110.9, 149.5, 171.7, 171.9, 199.8; LRMS (EI): 239 (1%) [M⁺], 209 (19%), 180 (18%), 152 (95%), 93 (100%); HRMS 209.0815 [209.0814 calcd for C₁₁H₁₃O₄(M⁺-CH₃O)].

4,4-Bis(methoxymethyl)-2-methylenecyclopentanecarbaldehyde (2i)

¹H NMR (250 MHz, CDCl₃): δ = 1.25 (s, 3 H), 1.46 (d, *J* = 14.2 Hz, 1 H), 2.18 – 2.41 (m, 3 H), 3.22 – 3.24 (m, 4 H), 3.32 (s, 3 H), 3.34 (s, 3 H), 4.87 (app. t, *J* = 2.1 Hz, 1 H), 5.12 (app. t, *J* = 2.0 Hz, 1 H), 9.32 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 22.5, 39.0, 40.3, 46.1, 56.9, 59.3, 59.4, 76.1, 76.2, 109.9, 152.7, 201.0; LRMS (EI): 212 (1%) [M⁺], 180 (5%), 180 (18%), 152 (8%), 119 (50%), 107 (100%).

4,4-Bis(benzyloxymethyl)-2-methylenecyclopentanecarbaldehyde (2j)

¹H NMR (250 MHz, CDCl₃): δ = 1.22 (s, 3 H), 1.53 (d, *J* = 14.1 Hz, 1 H), 2.25 – 2.48 (m, 3 H), 3.39 (m, 4 H), 4.50 (s, 2 H), 4.51 (s, 2 H), 4.85 (app. t, *J* = 2.1 Hz, 1 H), 5.10 (app. t, *J* = 1.9 Hz, 1 H), 7.27 – 7.37 (m, 10 H), 9.29 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 22.5, 39.1, 40.5, 46.3, 56.9, 73.3, 73.3, 73.4, 73.6, 109.9, 127.5, 127.6, 128.4, 138.8, 152.7, 200.9; LRMS (EI): 364 (1%) [M⁺], 273 (10%), 107 (35%), 91 (100%); HRMS 273.1489 [273.1491 calcd for C₁₇H₂₁O₃(M⁺-C₇H₇)].

2,3-Dihydro-2-methyl-1-methylene-1*H*-indene-2-carbaldehyde (2k)

¹H NMR (360 MHz, CDCl₃): δ = 1.42 (s, 3 H), 2.82 (d, *J* = 16.8 Hz, 1 H) 3.53 (d, *J* = 16.8 Hz, 1 H), 5.03 (s, 1 H), 5.71 (s, 1 H) 7.20–7.29 (m, 3 H), 7.46–7.50 (m, 1 H), 9.41 (s, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 10.9, 35.9, 121.8, 124.7, 127.1, 129.3, 139.7, 144.5, 144.9, 156.0, 187.3; 172 (52%) [M⁺], 143 (74%), 128 (100%), 115 (30%); HRMS: 172.0889 [172.0888 calcd for C₁₂H₁₂O (M⁺)].

Dimethyl 5,6,7,7a-tetrahydro-3-methyl-4-oxo-2*H*-indene-1,1(4*H*)-dicarboxylate (5)

¹H NMR (360 MHz, CDCl₃): δ = 1.11–1.22 (m, 1 H), 1.70–1.83 (m, 1 H), 1.99–2.23 (m, 6 H), 2.42–2.48 (m, 1 H), 2.77 (d, *J* = 18.4 Hz, 1 H), 3.10 (d, *J* = 18.4 Hz, 1 H), 3.68–3.71 (m, 1 H), 3.72 (s, 3 H), 3.75 (s, 3 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 15.9, 23.6, 27.7, 40.8, 46.3, 52.1, 52.4, 52.9, 62.1, 132.1, 149.6, 170.9, 171.9, 199.3; LRMS (EI): 266 (54%) [M⁺], 206 (70%), 147 (100%), 119 (26%); HRMS: 266.1153 [266.1154 calcd for C₁₄H₁₈O₅(M⁺)].

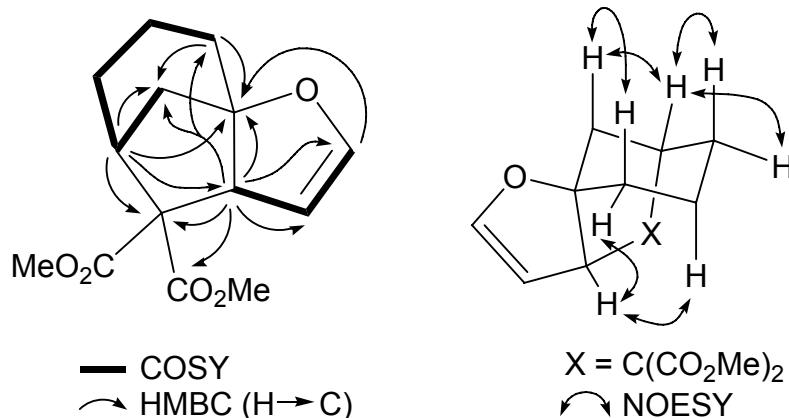
Dimethyl 4,5,6,6a-tetrahydro-3-methyl-4-oxopentalene-1,1(3a*H*)-dicarboxylate (8**)**

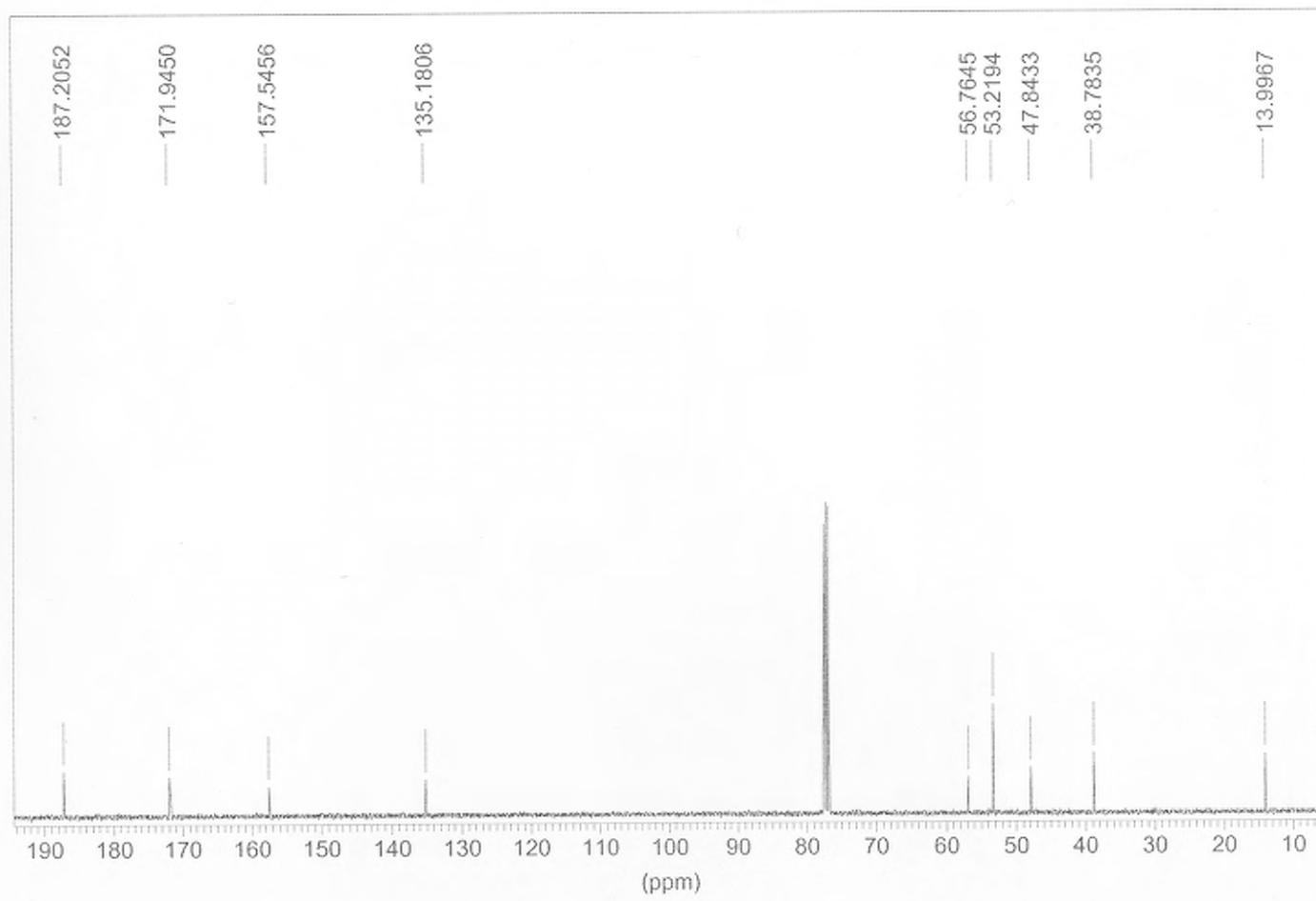
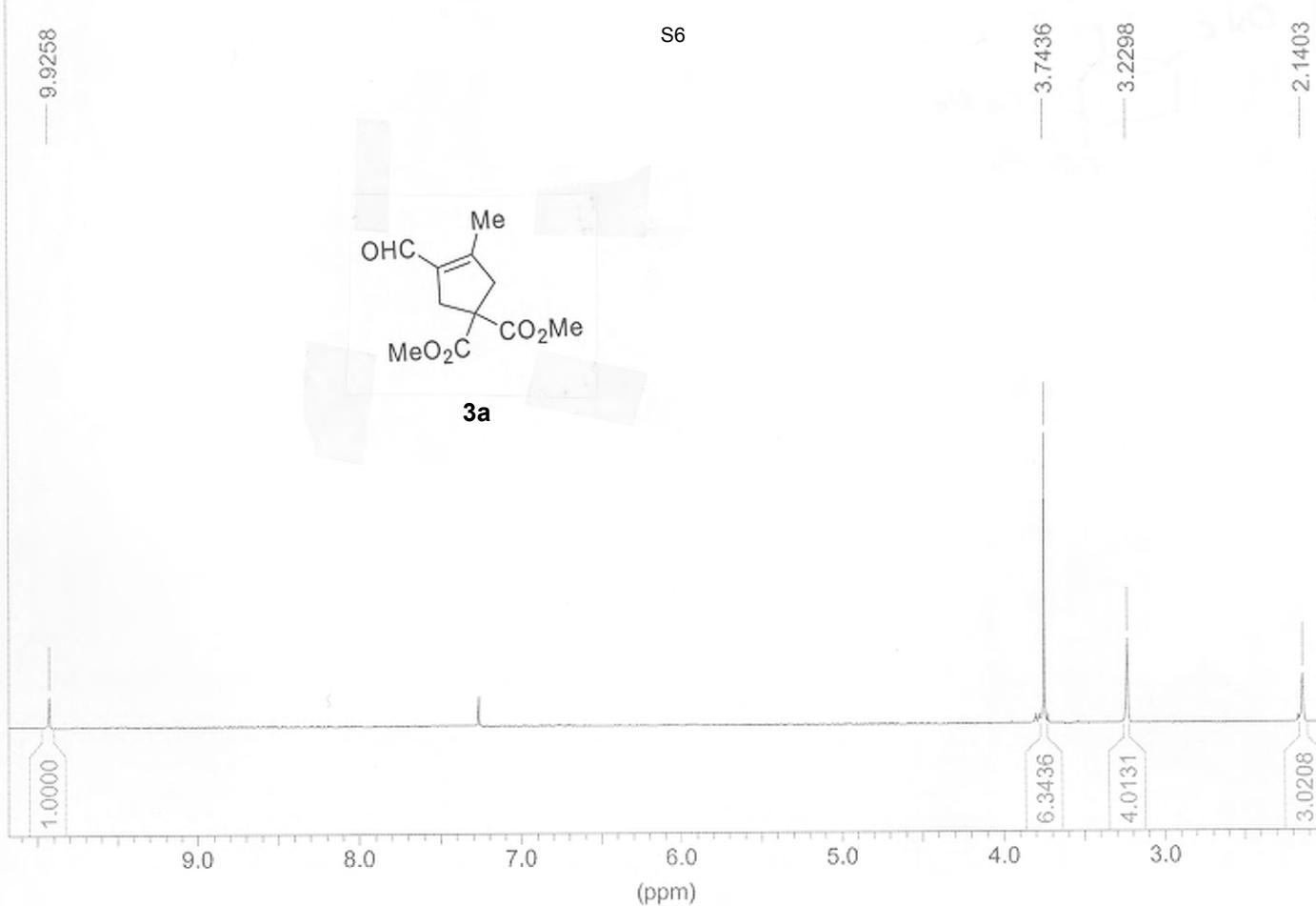
¹H NMR (360 MHz, CDCl₃): 1.46–1.55 (m, 1 H), 1.77–1.78 (m, 3 H), 197–2.07 (m, 1 H), 2.18–2.24 (m, 2 H), 3.27–3.29 (m, 1 H), 3.58–3.65 (m, 1 H), 3.67 (s, 3 H), 3.72 (s, 3 H), 5.49–5.51 (m, 1H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 14.7, 24.0, 38.6, 45.1, 52.5, 53.0, 61.4, 69.3, 124.3, 142.4, 170.2, 170.7, 215.2; LRMS (EI): 252 (62%) [M⁺], 193 (100%), 164 (62%), 105 (60%); HRMS: 252.0998 [252.0999 calcd for C₁₃H₁₆O₅ (M⁺)].

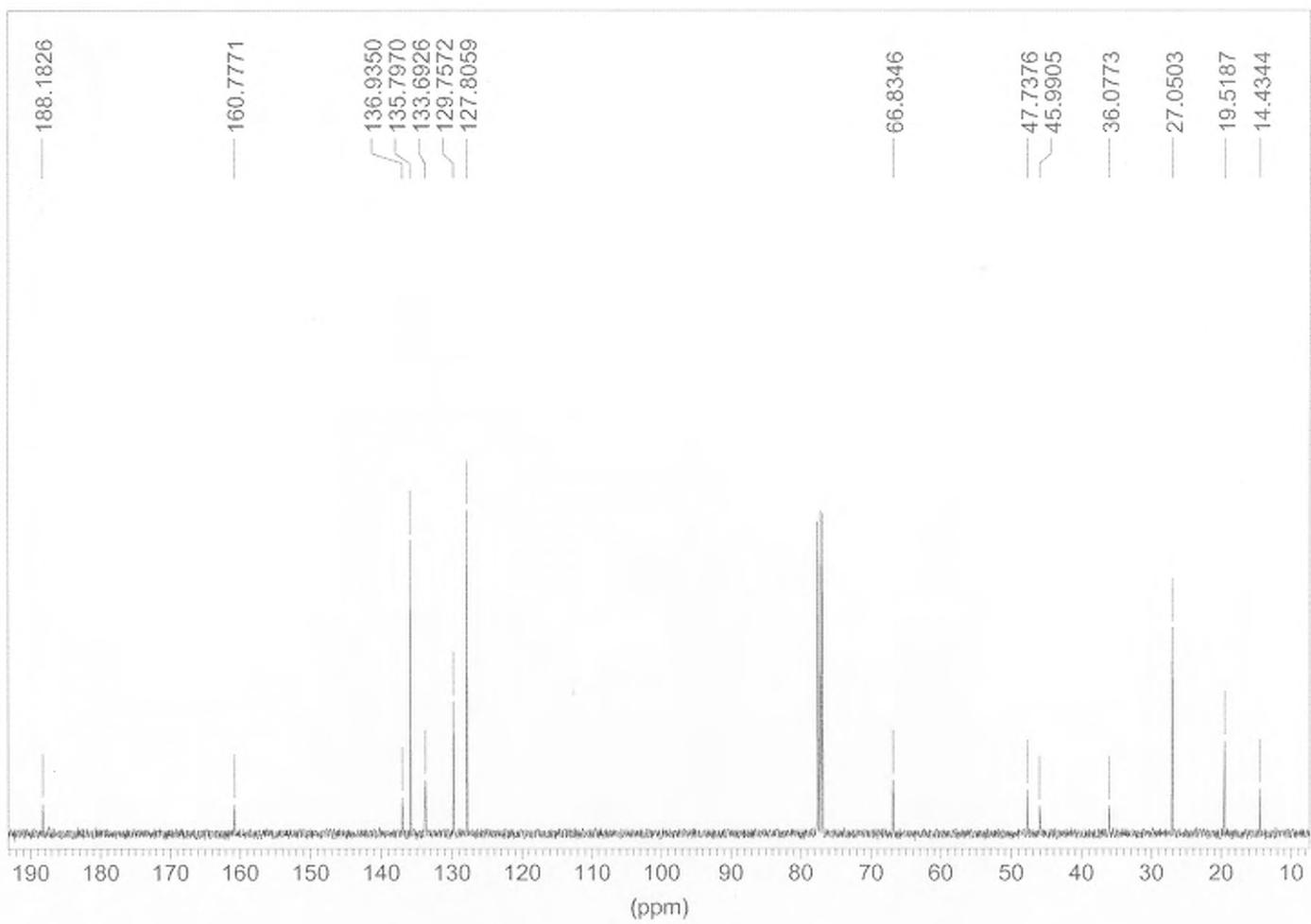
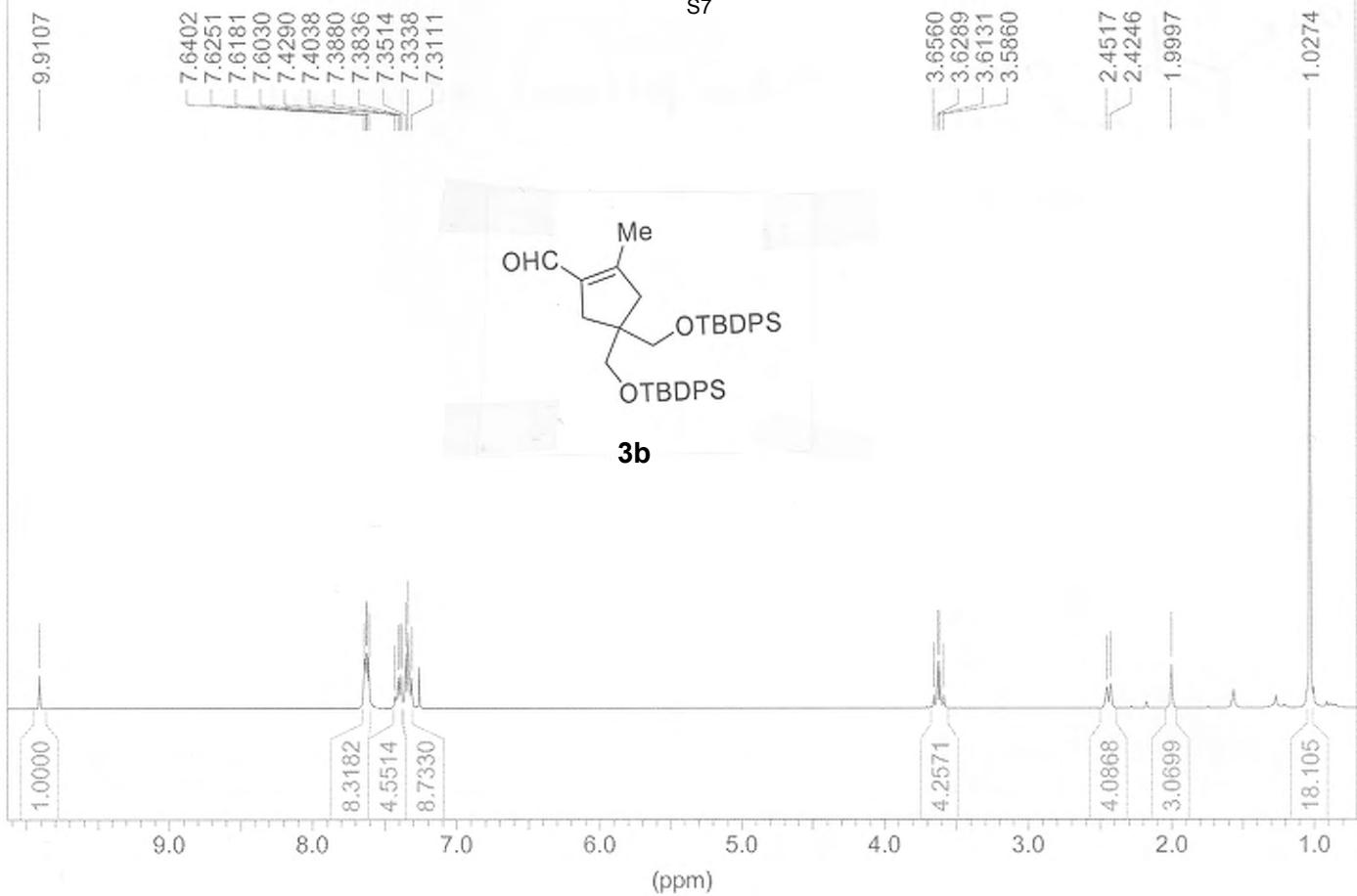
5-Methyl-2-oxa-tricyclo[5.3.1.0^{1,5}]undec-3-ene-6,6-dicarboxylic acid dimethyl ester (9**)**

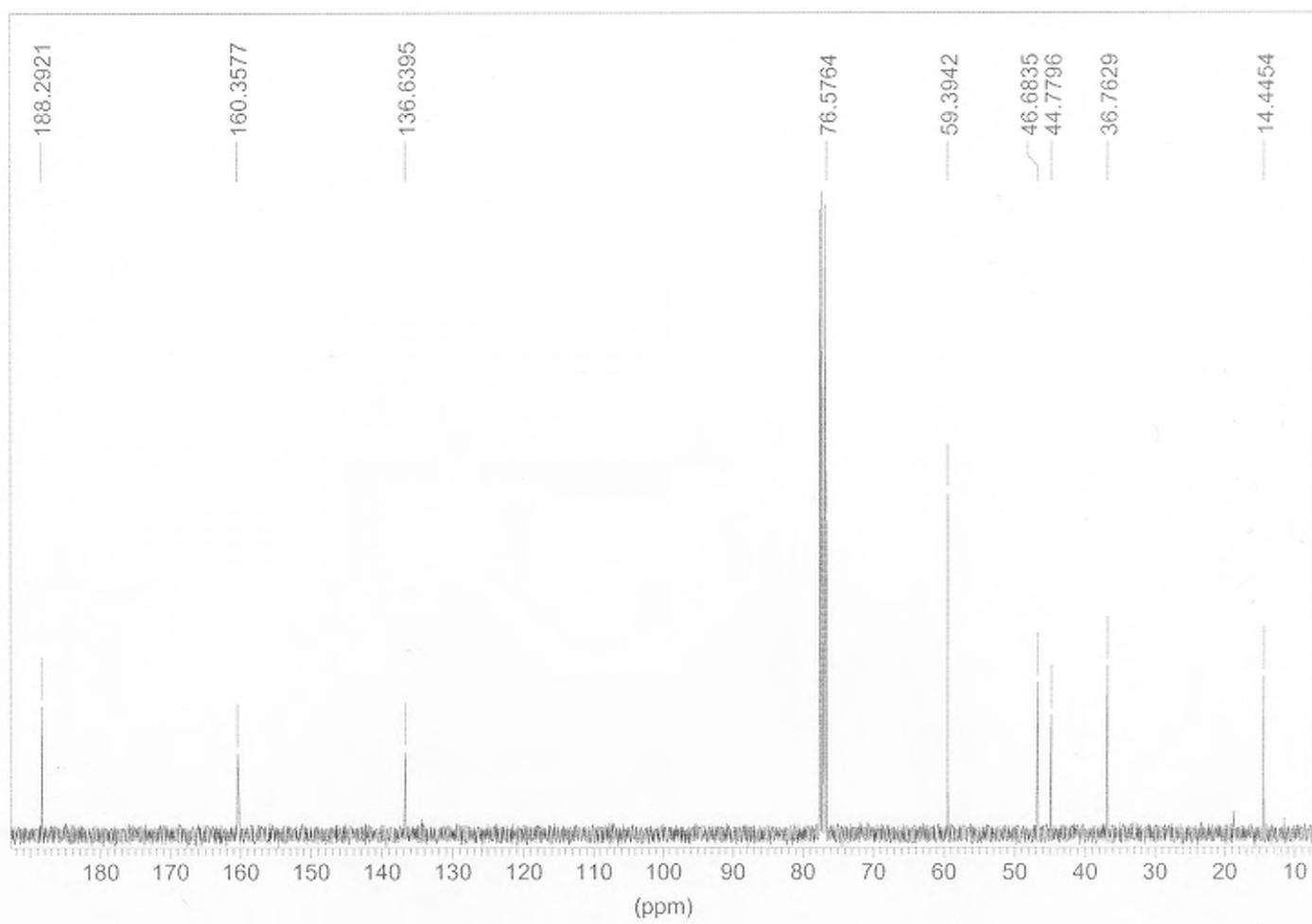
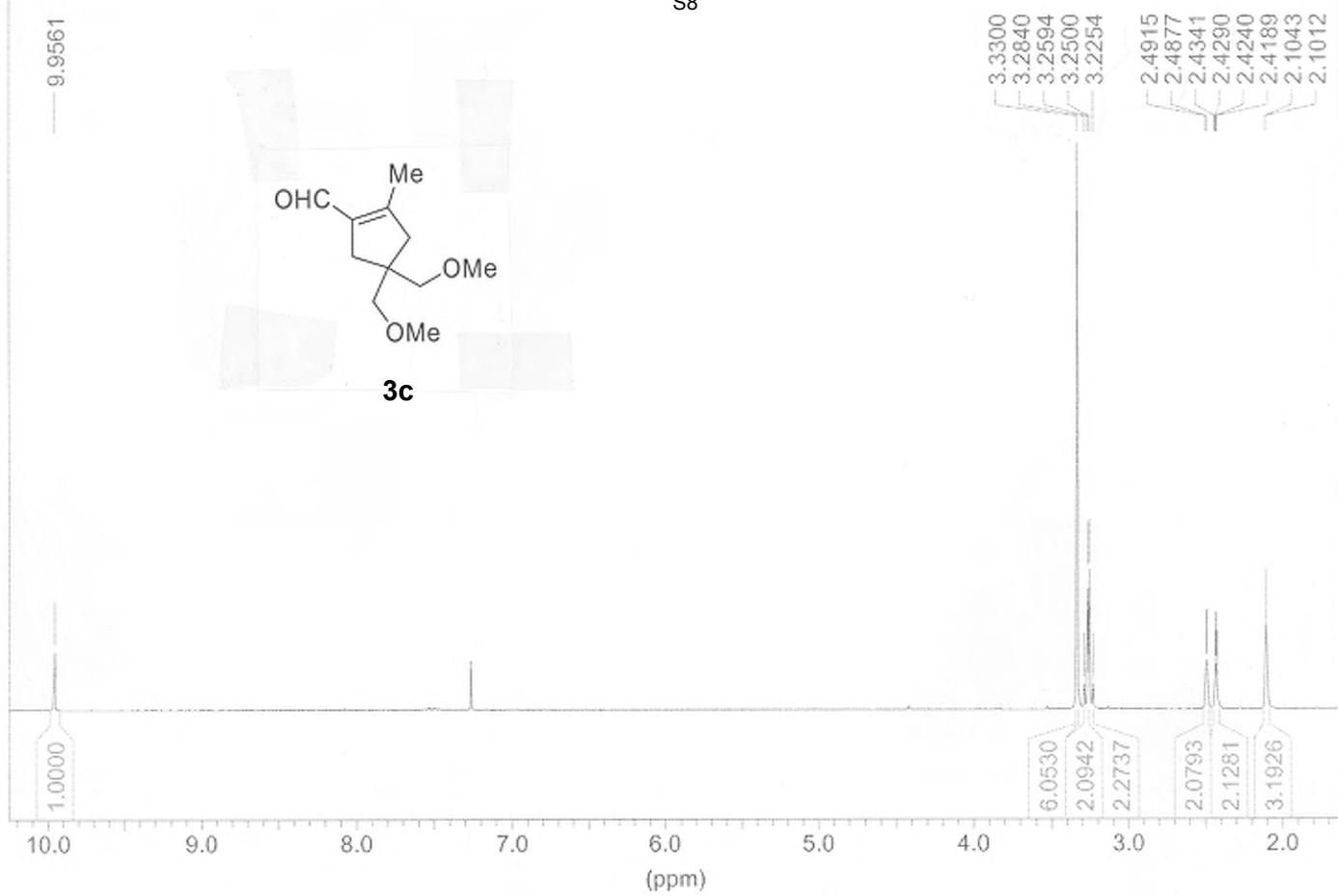
¹H NMR (360 MHz, CDCl₃): δ = 1.32–1.40 (m, 1 H), 1.41–1.51 (m, 1 H), 1.53–1.63 (m, 2 H), 1.65–1.74 (m, 1 H), 1.80–1.86 (m, 1 H), 1.91–1.99 (m, 1 H), 2.36–2.41 (m, 1 H), 2.79–2.82 (m, 1 H), 3.71 (s, 3 H), 3.74 (s, 3 H), 4.01–4.03 (m, 1 H), 4.73 (t, *J* = 2.3 Hz, 1 H), 6.21 (t, *J* = 2.3 Hz, 1 H); ¹³C NMR (90.6 MHz, CDCl₃): δ = 19.9, 27.7, 34.6, 42.7, 43.4, 52.2, 52.6, 53.4, 66.6, 93.3, 101.0, 146.2, 170.6, 170.7; LRMS (EI): 266 (81%) [M⁺], 234 (100%), 206 (95%), 134 (82%); HRMS: 266.1156 [266.1154 calcd for C₁₄H₁₈O₅ (M⁺)].

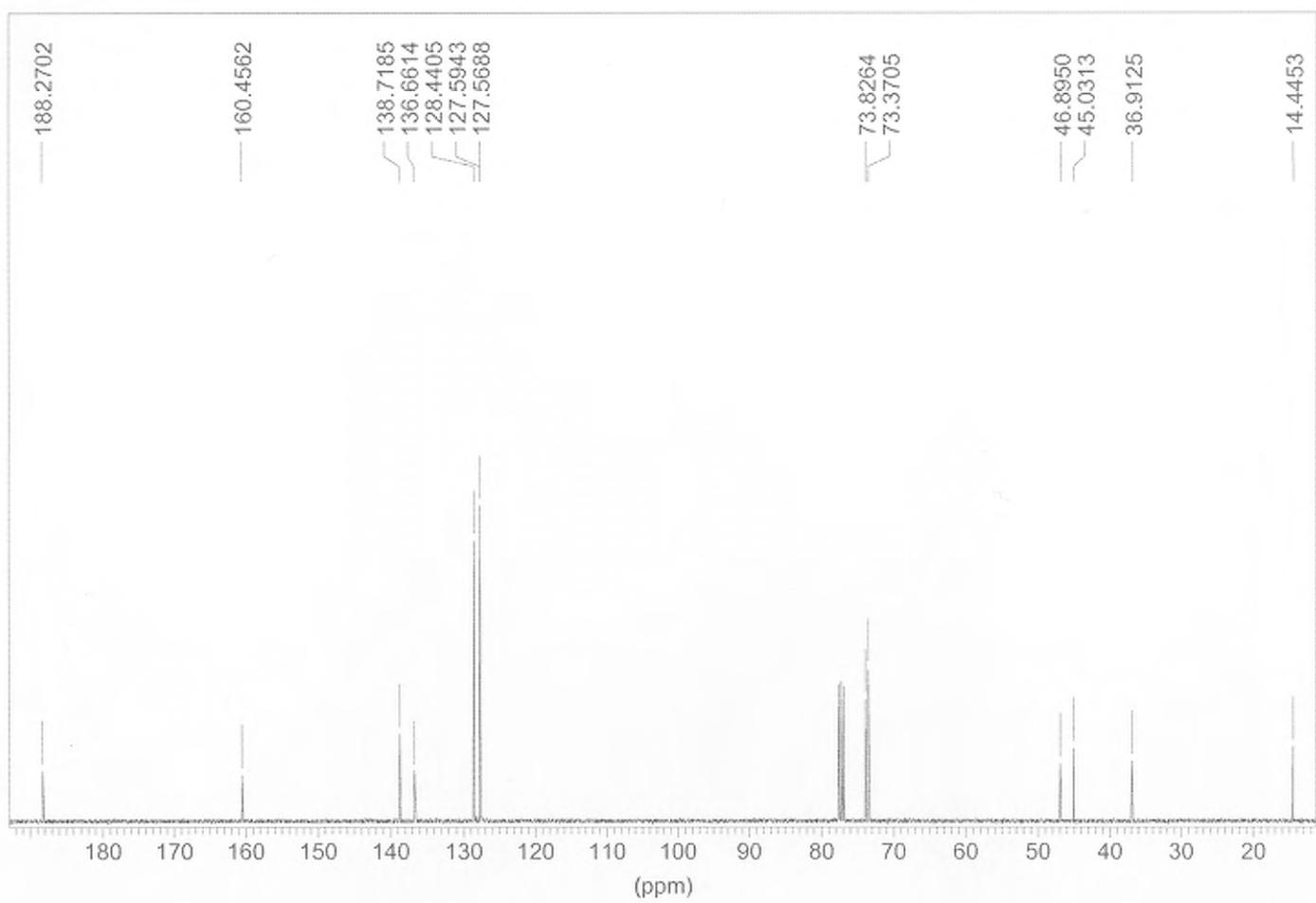
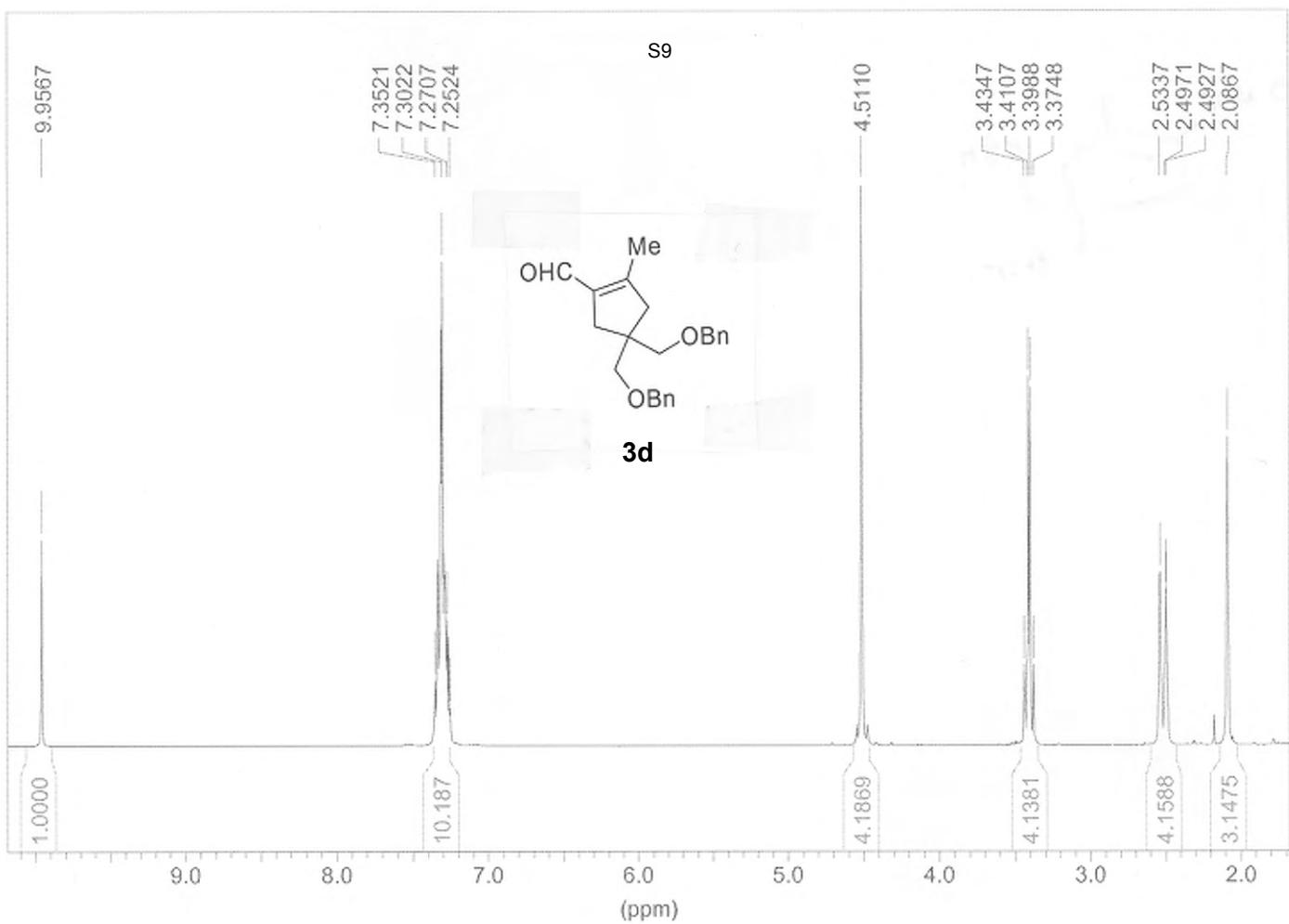
Key COSY, HMBC, and NOESY correlations of **9** are given in the illustration:

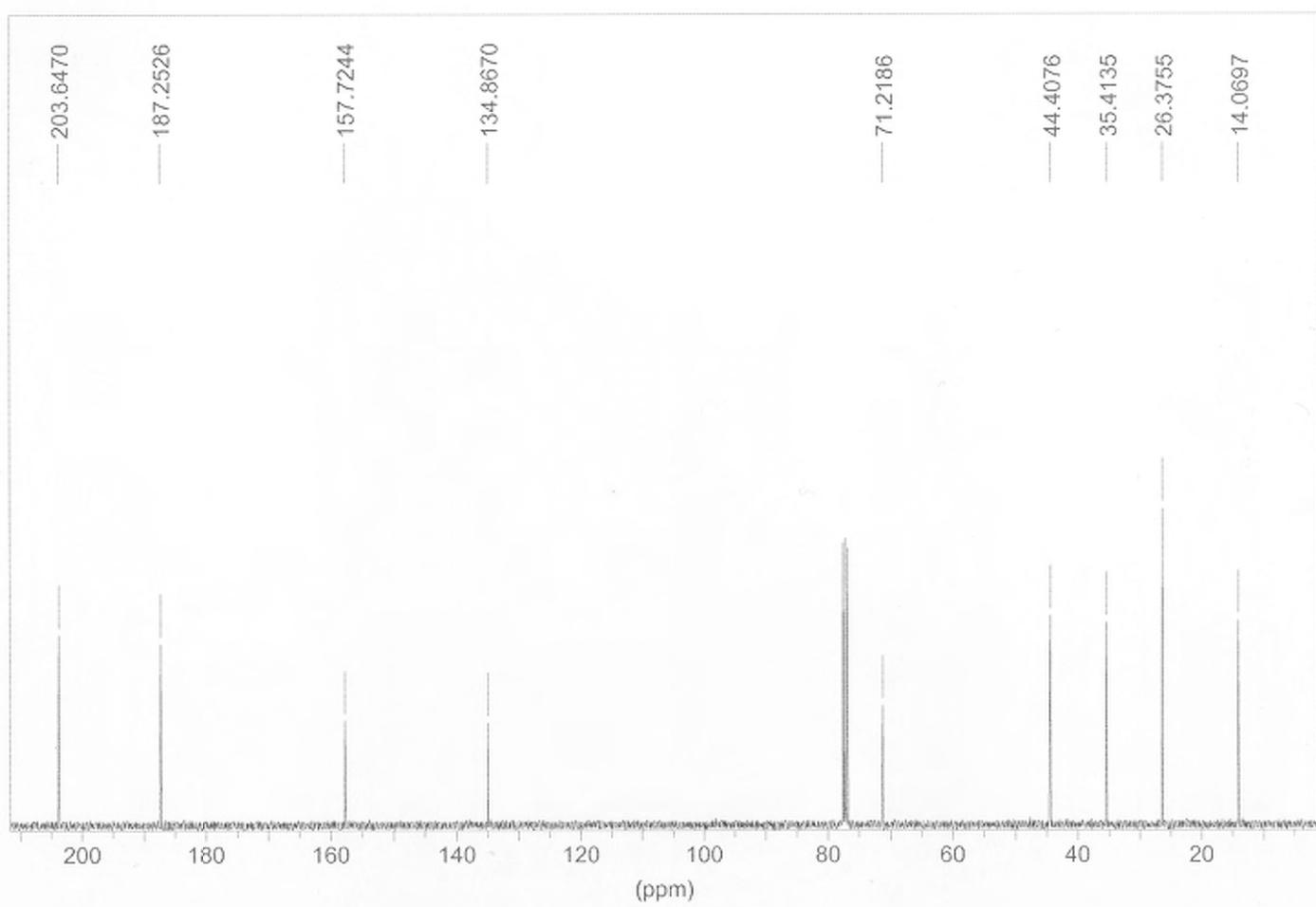
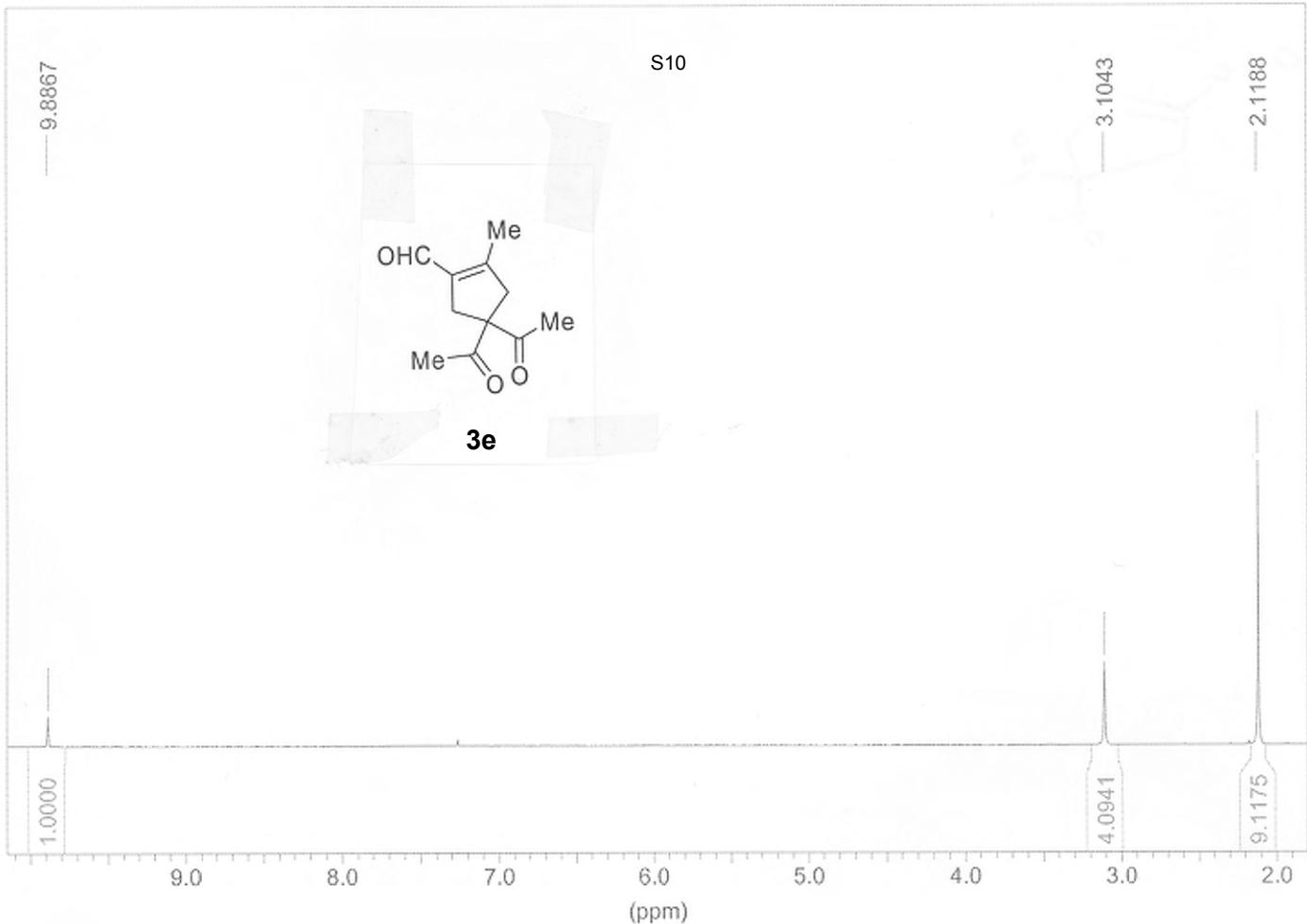


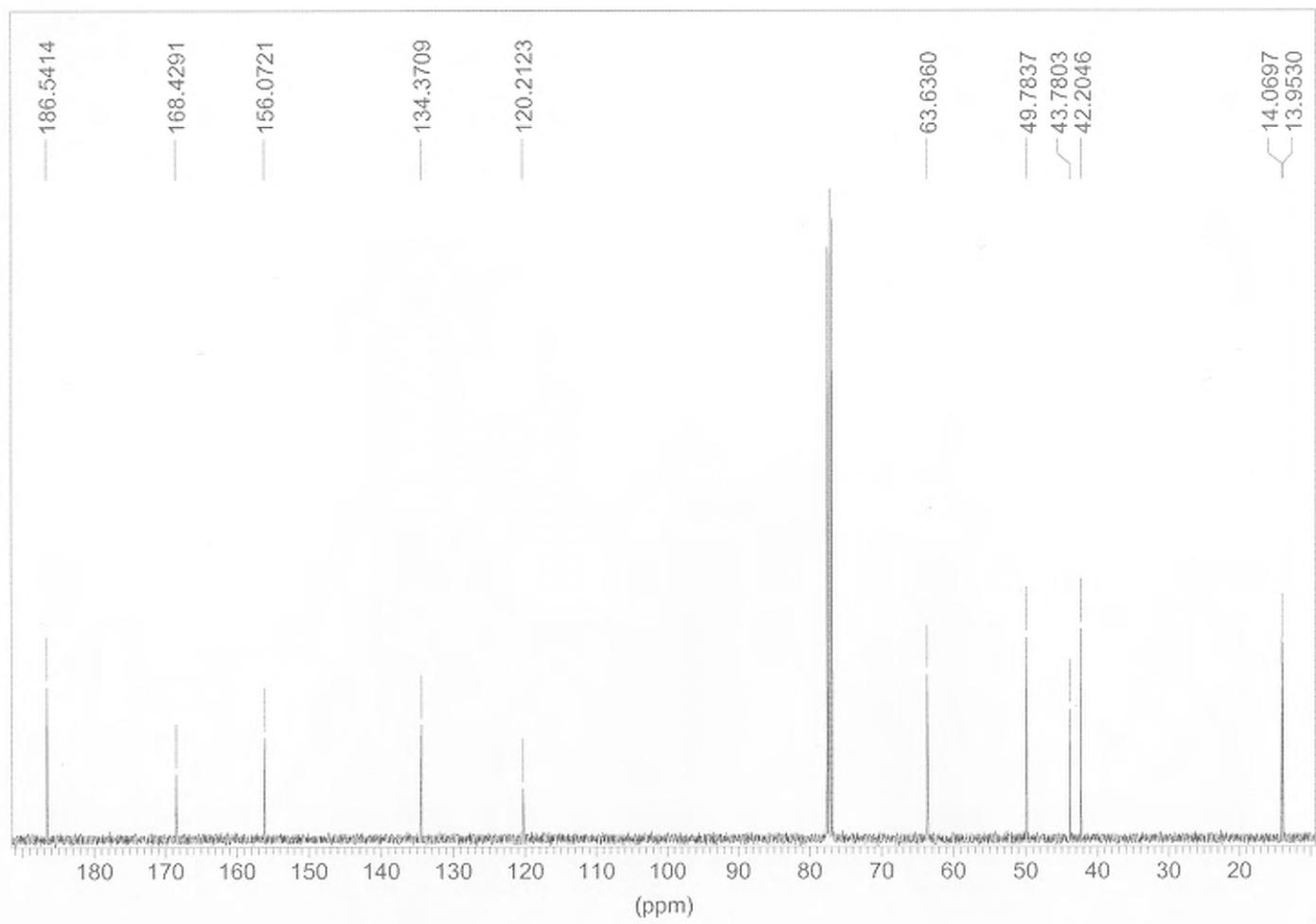
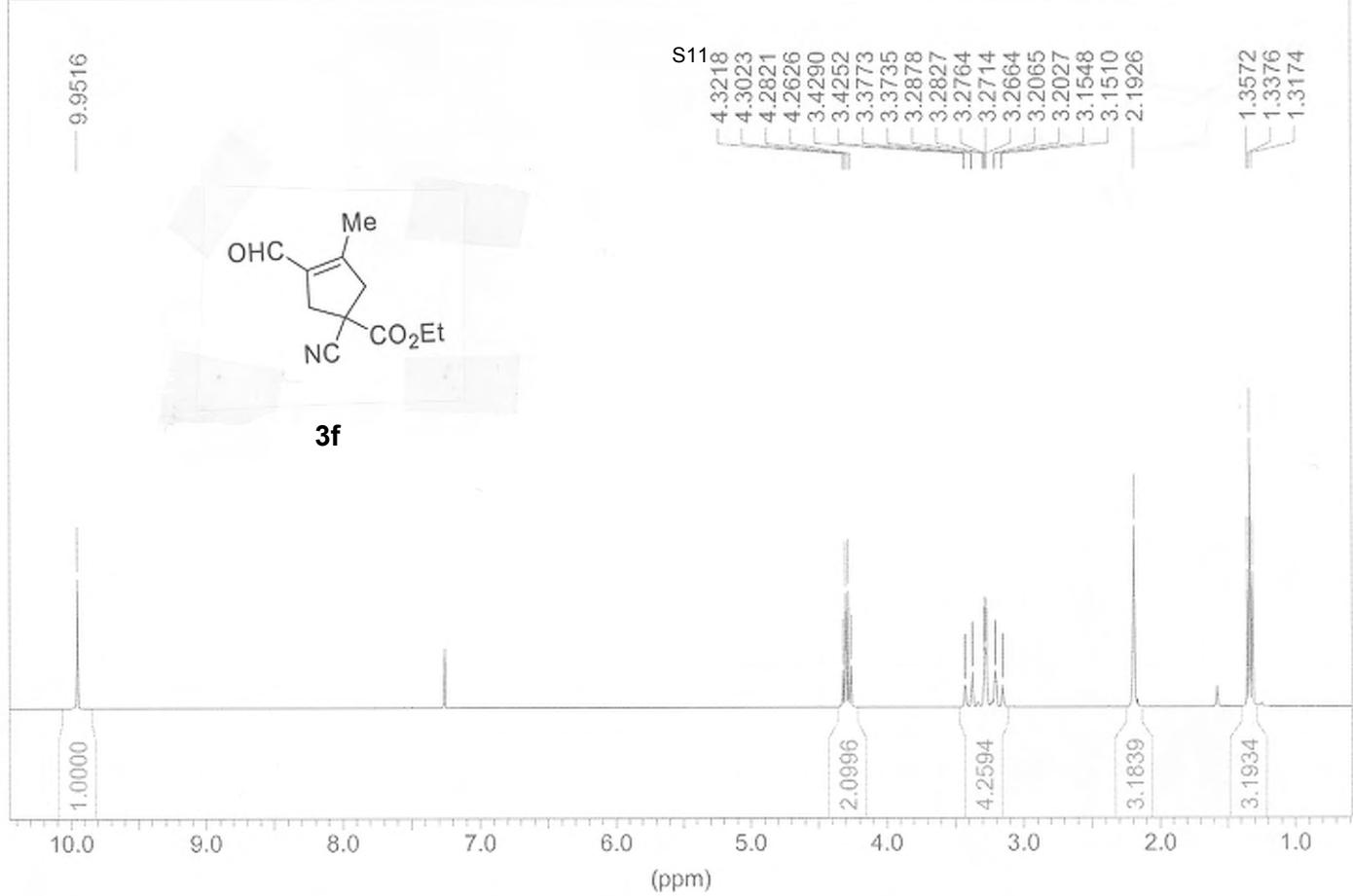


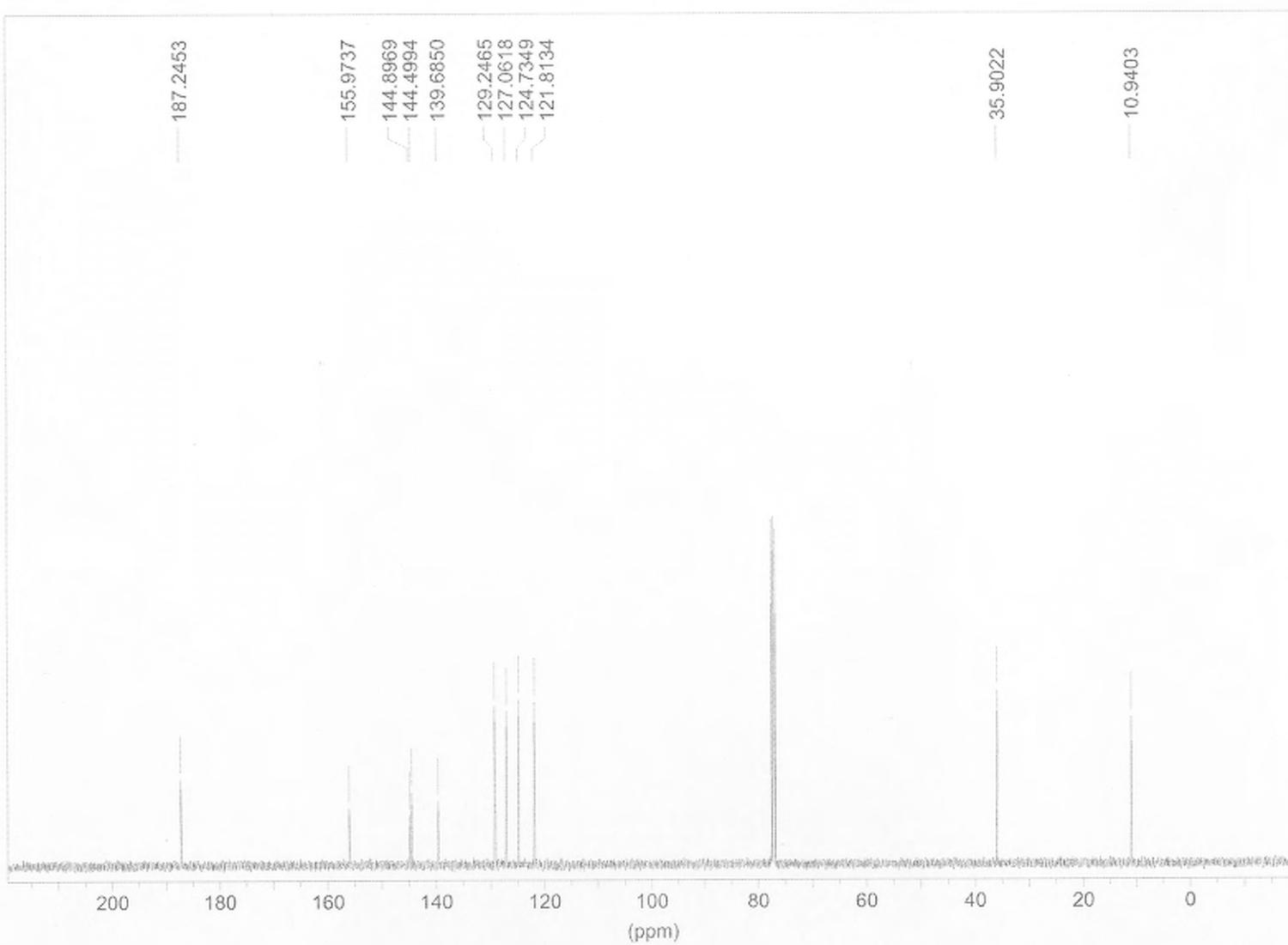
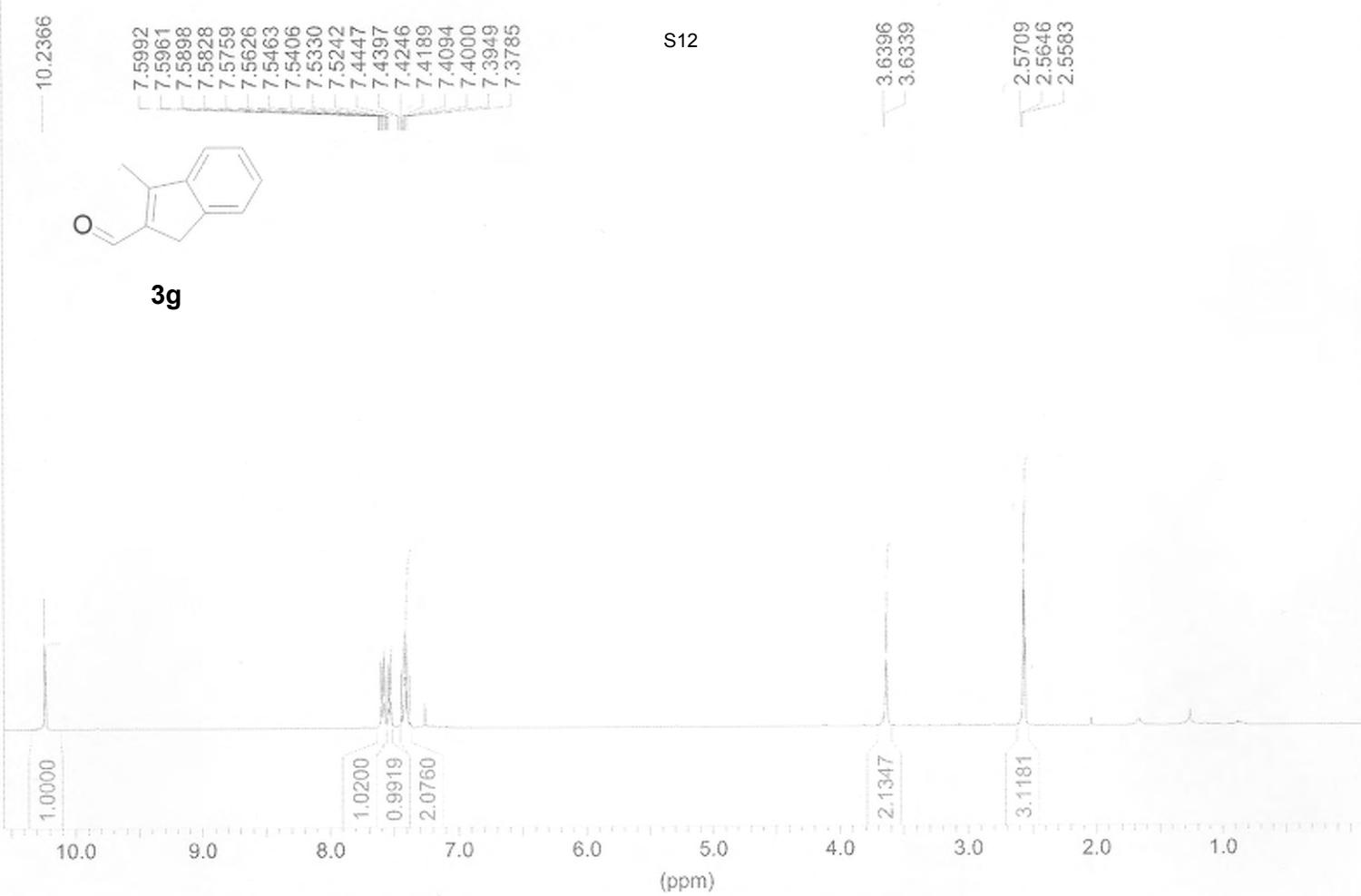


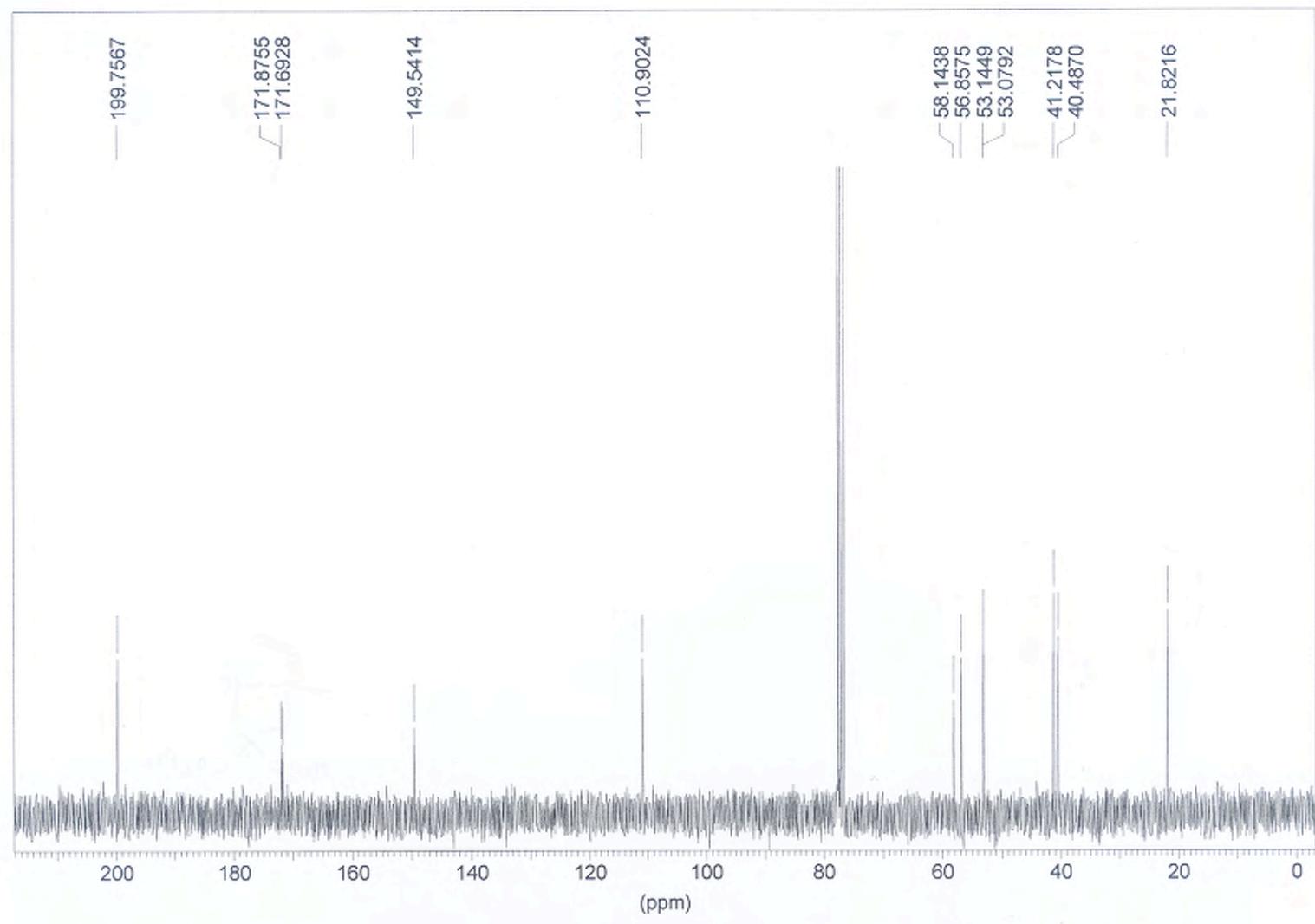
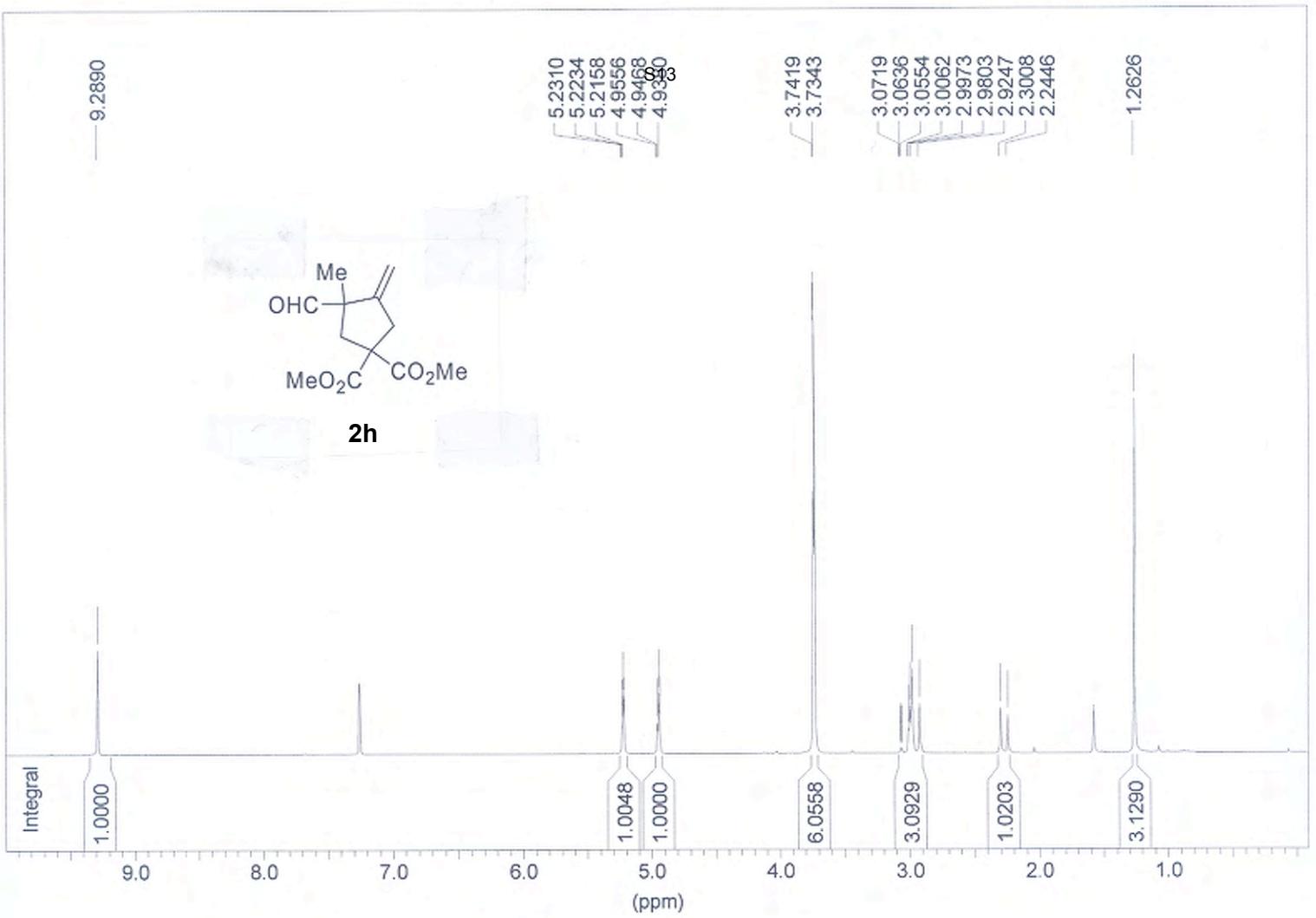




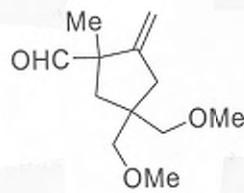




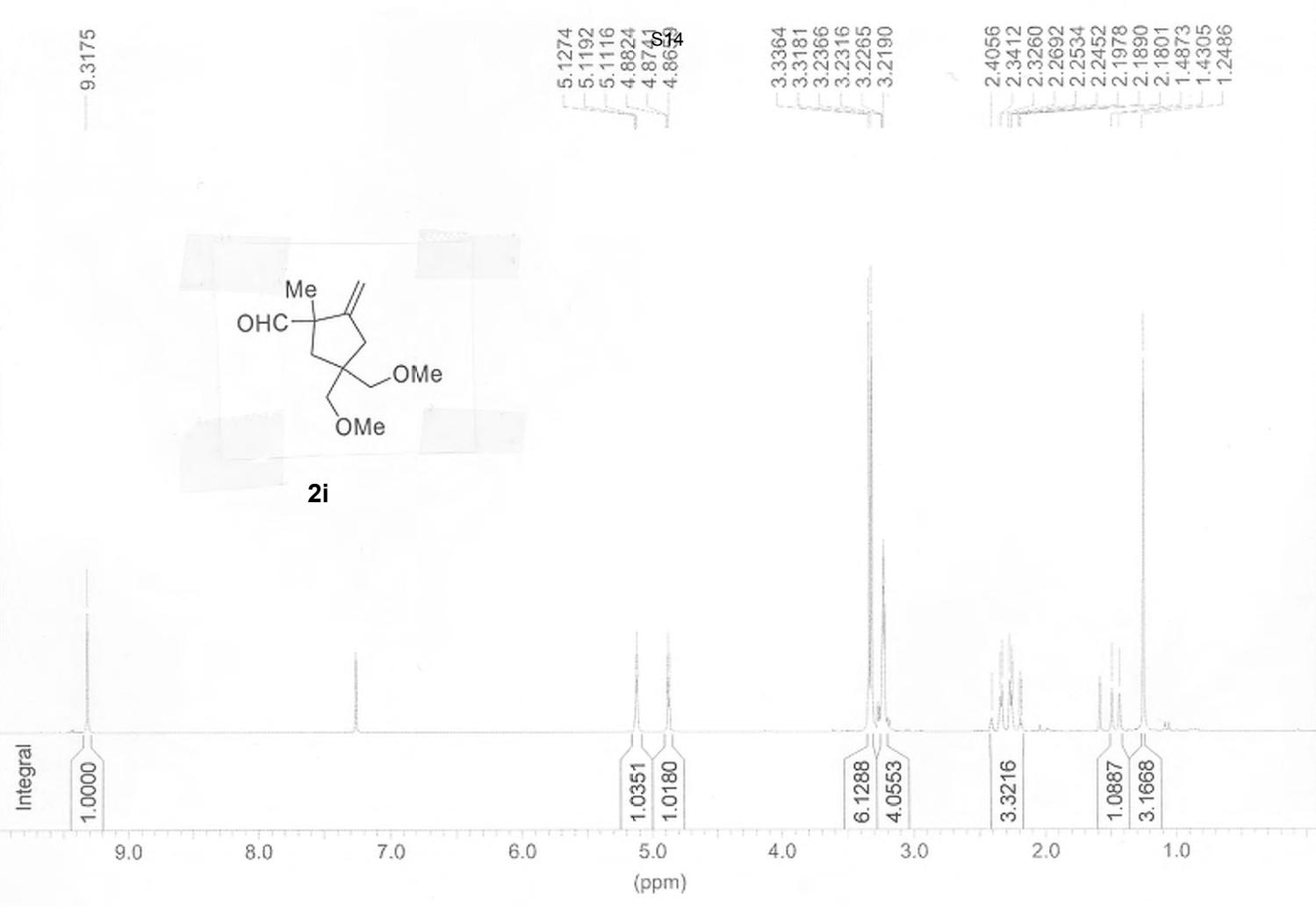




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2i



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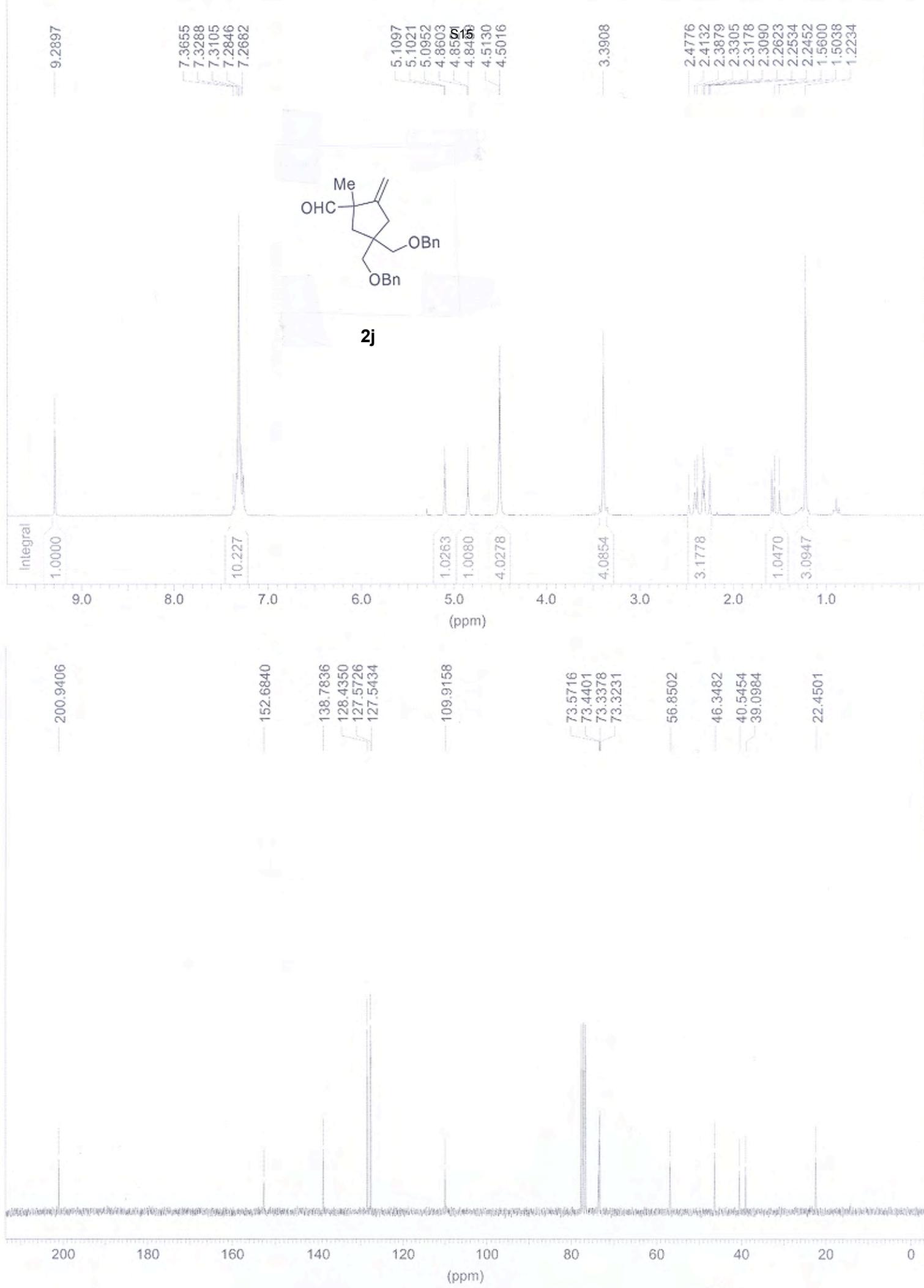
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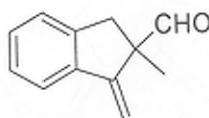
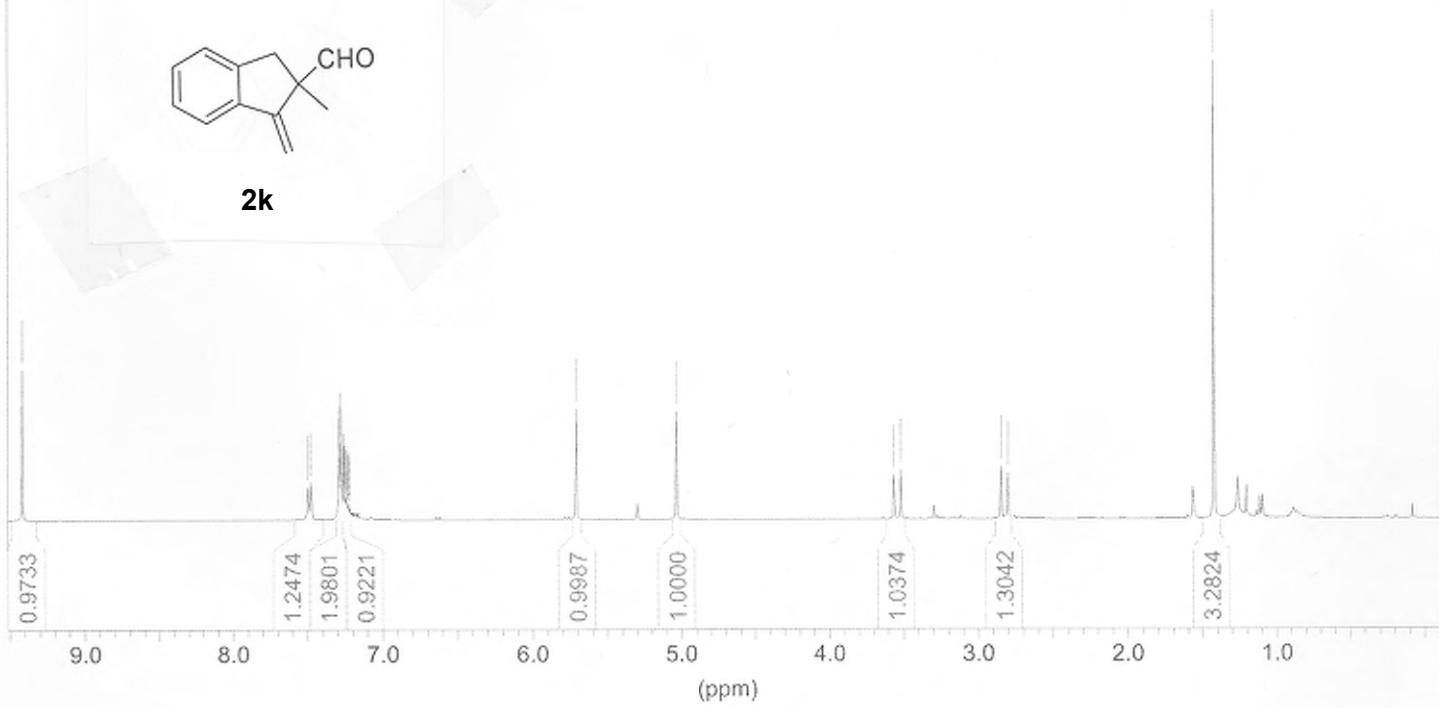
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**2k**

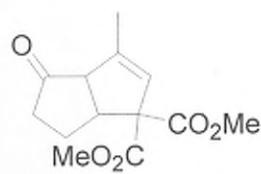
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(ppm)



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Integral

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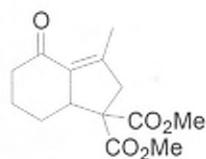
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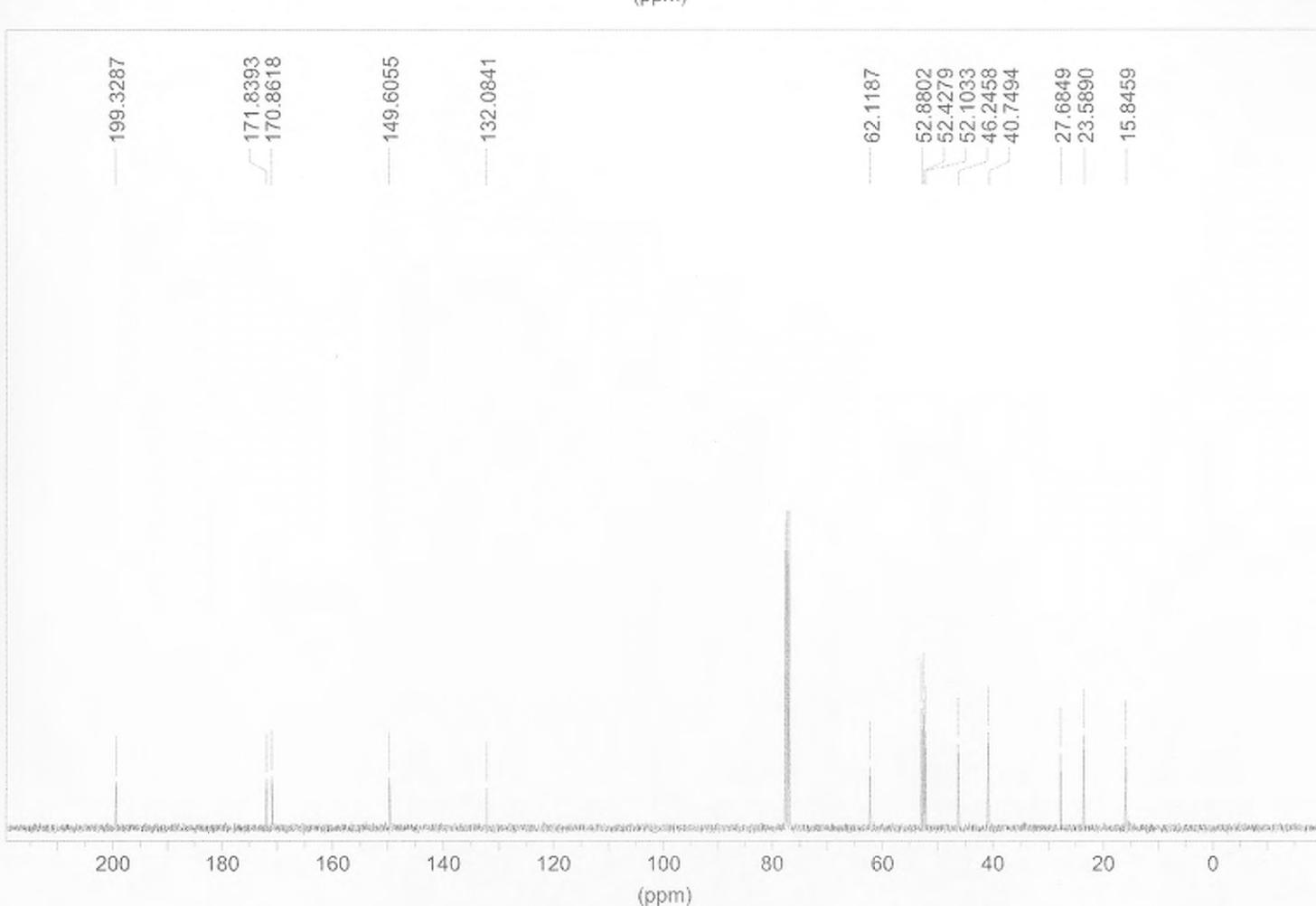
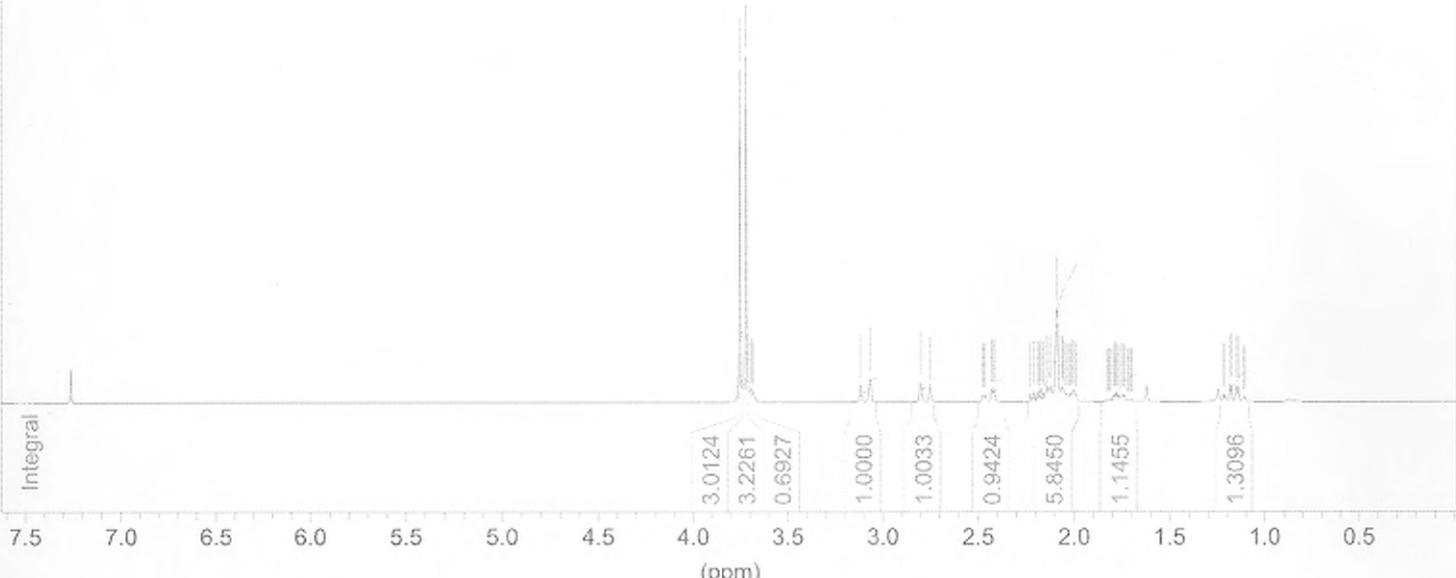
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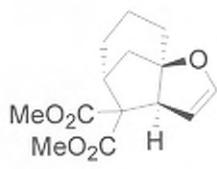
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1.1157
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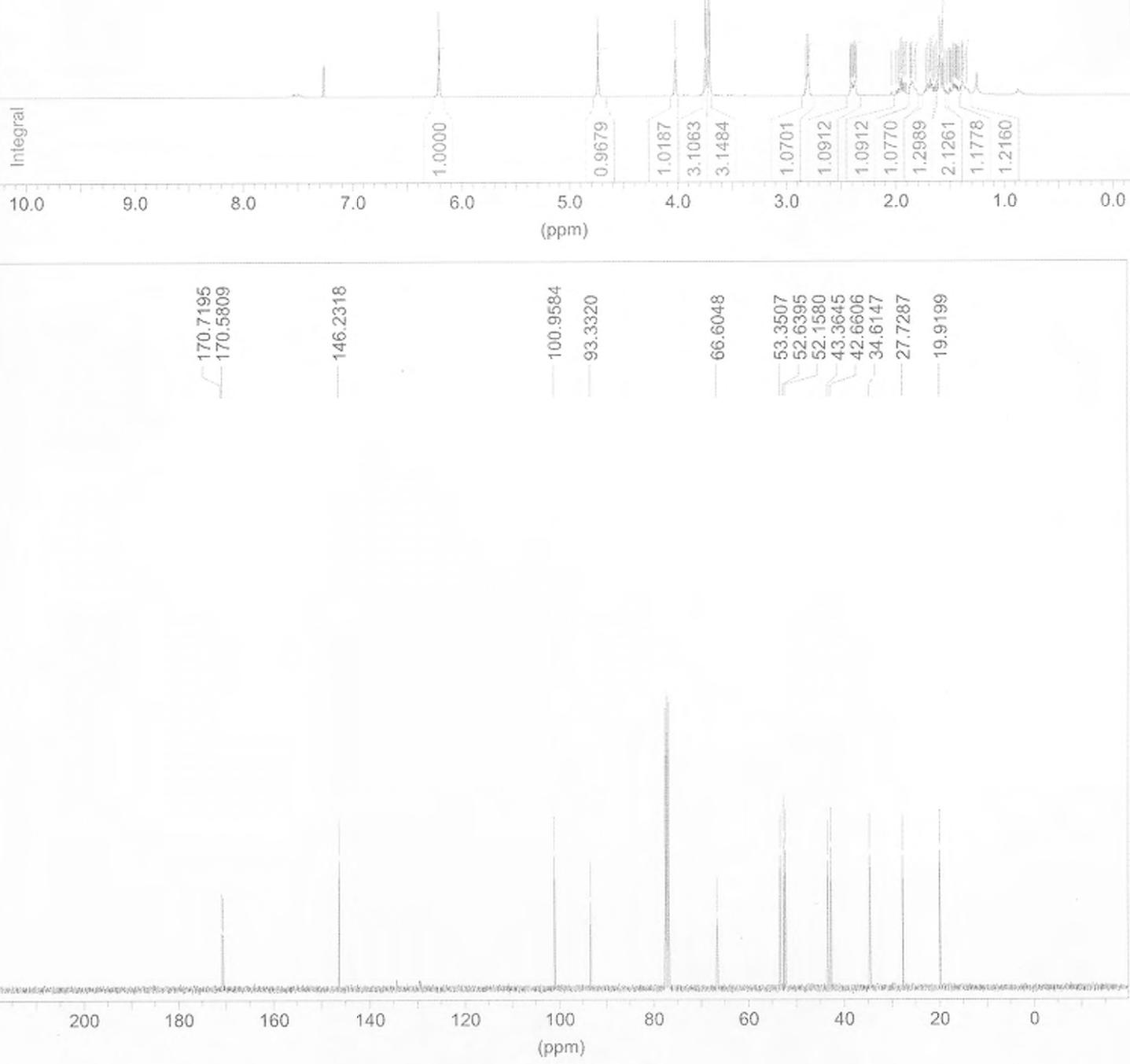
5



6.2077	6.2007	4.7405	4.7342	4.0179	3.7373	3.7058	2.8200	2.8111	2.7991	2.7910	2.4133	2.4063	2.4000	2.3931	2.3843	2.3761	2.3692	2.3553	2.0356	1.9889	1.9719	1.9555	1.9385	1.9227	1.9051	1.8641	1.884	1.19	1.158	1.8124	1.7203	1.6989	1.6806	1.6668	1.6504	1.6340	1.6163	1.5930	1.5823	1.5621	1.5432	1.5268	1.5066	1.4984	1.4889	1.4801	1.4681	1.4593	1.4492	1.4404	1.4347	1.4259	1.4158	1.4070	1.3893	1.3761	1.3465
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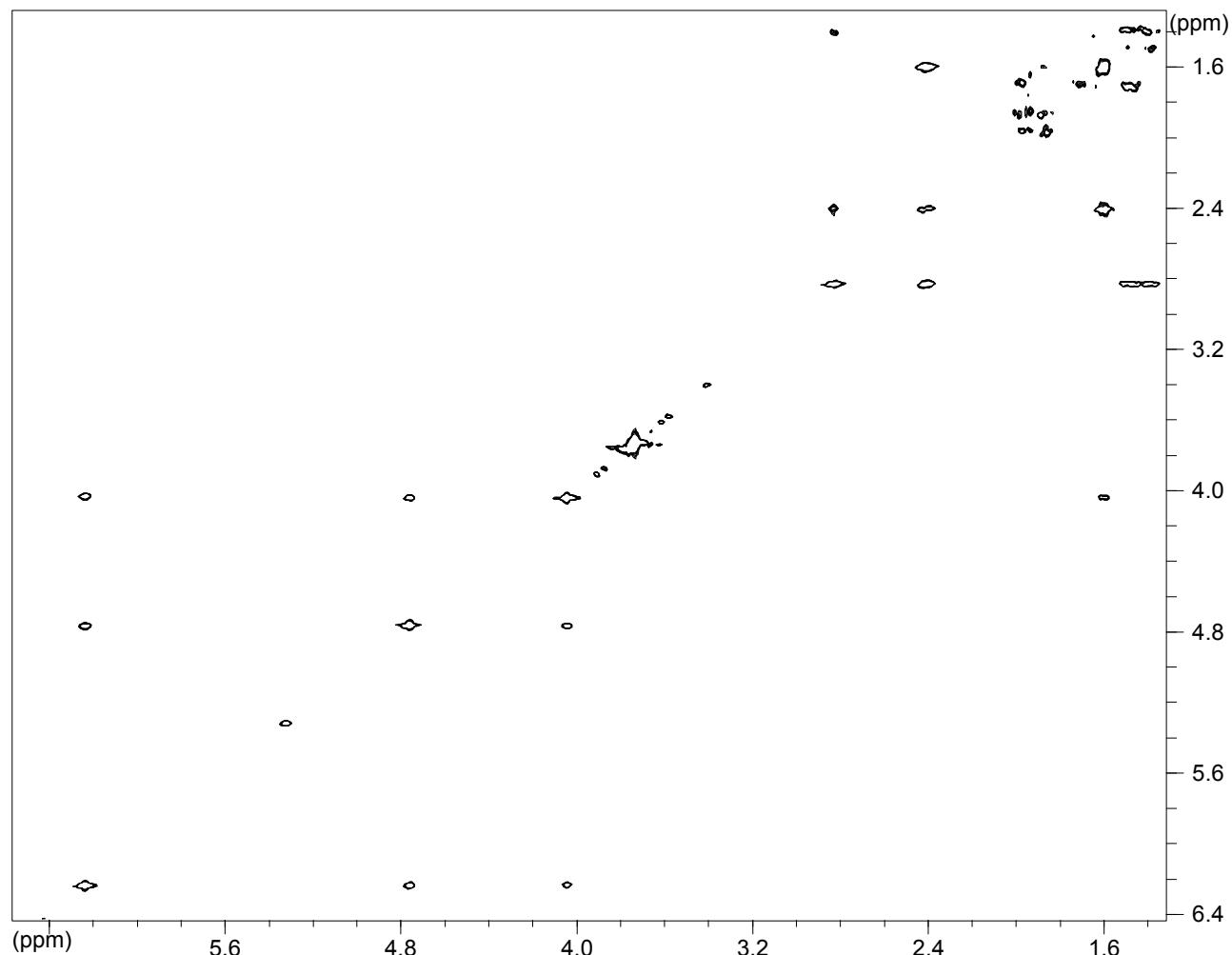
9



The Bruker logo, featuring the word "Bruker" in red with a blue swoosh graphic above it.

*** Current Data Parameters ***

NAME	:	bciii79f1
EXPNO	:	11
PROCNO	:	1





*** Current Data Parameters ***

NAME	:	bciii79f1
EXPNO	:	13
PROCNO	:	1

